November 1973 LRP 74/73

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A b s t r a c t

The Curved Theta Pinch Experiment, which uses an oscillating axial current to establish a toroidal equilibrium, has been modified by introducing quartz limiters at the ends of the discharge tube . This report describes recent measurements on the new version of the device. In contrast to previous experiments, we observe that the oscillating axial current flows mainly through the dense plasma column.

Lausanne

I. Introduction

Toroidal high beta confinement systems have been investigated for quite some time at a number of laboratories. Several methods for producing stable, toroidal equilibria have been proposed [1-3] . The scheme that we are studying at Lausanne consists of a theta pinch which is curved to form a segment of a torus, with an oscillating axial current. Previous measurements in this device [4] have shown that the oscillating I_z current suppresses the usual toroidal drift of the plasma column and allows a stable, dynamic, high beta equilibrium to be established, even though the r.m.s. value of the axial current considerably exceeds the Kruskal-Shafranov limit.

However, the measurements [4] have also shown that the axial current tends to flow in the dilute plasma close to the wall, rather than on the dense plasma column. In addition, very large anomalous resistivity has been observed [4, 5]. As a consequence, high frequency power dissipation is excessive and it appears questionable whether this scheme could be applied to the production and confinement of a thermonuclear plasma.

Recently, it has been conjectered [6] that if the Alfven speed in the dilute plasma is sufficiently large, limiters will cause the oscillating B_θ field to penetrate onto the dense column. In order to test this idea experimentally, we have modified the apparatus by installing quartz limiters at both ends of the discharge tube, close to the axial electrodes.

The new version of the experimental apparatus is described in section II and measurements are presented in section III.

II. Experimental Apparatus

Fig. 1 is a schematic diagram of the new version of the apparatus. Note the two limiters at the ends of the discharge tube. Their free diameter (1.4 cm) was chosen roughly equal to the diameter of the plasma column, as seen on streak photographs. The important experimental parameters are listed in Table I.

Table I : Experimental Parameters

Internal diameter of discharge tube	5	cm
Length of discharge tube	70	cm
Radius of toroidal curvature	187	cm
Maximum B_z magnetic field	18	KG
$\tau/4$ for theta pinch discharge	4.3	μs
Oscillating axial current, $\tilde{I}_z$ (r.m.s.)	6	KA
Frequency of $\tilde{I}_z$ current	0.5	MHz
Duration of I_z pulse	6	μs
Filling gas and pressure	D_2 , 40 mTorr	

Deuterium gas at a pressure of 40 mTorr was allowed to flow continuously through the discharge tube. Preionization of the gas was achieved by discharging a 7.7μF capacitor between the two end electrodes. The charging voltage was 11 KV and the discharge was damped by means of non linear resistors. This gave a half-sine current pulse having a maximum value of 18 KA and a 3 μs rise time. The main theta pinch discharge was triggered 10 μs after the start of the preionization pulse. The theta pinch coil, consisting of eight identical sections, was energized by a 55 μF capacitor bank, charged to 18 KV. The oscillating axial current, $\tilde{I}_z$, was supplied by a line generator of the type developed in this laboratory in recent years [7] . The line generator was triggered 1 μs ahead of the main theta-pinch discharge. Its characteristics are given in Table I.

III. Measurements

1. Density

The average mass density in the central plasma column can be deduced from measurements of the natural oscillation frequency of the pinch. If one considers adiabatic compression of a cylindrical plasma column with surface currents on the plasma-vacuum interface, one finds that the radial oscillation frequency is given by

$$\omega^2 = \frac{8}{\rho R^3}\left(\frac{B^2}{2\mu_0}\right)\left(1 - \frac{\beta}{6}\right) \qquad (1)$$

where ρ is the mass density ($\rho = n\, m_i$), R is the equilibrium radius of the column, and B is the confining magnetic field. β is usually quite small ($\beta \sim 30$ %), and has little effect on ω. The radius R is estimated from streak photographs, such as the ones shown in Fig. 2 ; ω and B are obtained from magnetic probe measurements. At 2.5 μs after the initiation of the pinch, for example, we have $\omega = 5.7 * 10^8$ sec^{-1} and B = 14.4 kG. Using R = 0.65 cm and $\beta = 0.3$, we obtain from equation (1): $\rho = 0.70 * 10^{-4}$ kg m^{-3} and

$$n = 2.10 * 10^{22} \text{ m}^{-3} \qquad (\pm 20\ \%)$$

The total mass per unit length of the plasma column is then given by $\rho\pi R^2$ = $0.79 * 10^{-8}$ kg m^{-1} which corresponds to 46 % of the filling gas (40 mTorr D_2).

2. Temperature

From a measurement of the drift of the plasma column to the outside wall of the discharge tube in the absence of $\tilde{I}_z$, one can deduce a mean plasma temperature, $k(T_e + T_i)$, i.e., a temperature which is averaged over the plasma radius and over the drift time. The mean temperature is given by

$$k\,(T_e + T_i) = \frac{R_W\, R_T\, m_i}{\tau_W^2} \tag{2}$$

where R_W is the internal radius of the discharge tube, R_T is the radius of toroidal curvature, m_i is the ion mass and τ_W is the drift time to the wall. From Fig. 2, we obtain τ_W = 3.5 μs and, using the geometrical parameters of our pinch, we have

$$k\,(T_e + T_i) = 80 \text{ eV.}$$

3. Beta

Beta values can be obtained in two different ways: (1) from average density and mean temperature measurements, and (2) from magnetic probe measurements of the field component B_z. For our pinch, at 2.5 μsec after the initiation of the main discharge, the first method gives

$$\beta = \frac{n k\,(T_e + T_i)}{\frac{\beta^2}{2\mu_0}} = 0.32 \pm 30\,\% .$$

The second method requires a measurement of the magnetic field strengths inside and outside the plasma column. We find, again at 2.5 μsec,

$$\beta = 1 - \left(\frac{B_i}{B_0}\right)^2 = 0.28 \pm 10\,\%$$

which agrees reasonably well with the first result.

4. Toroidal Shift

The equilibrium shift Δ, as seen on streak photographs (Fig. 2) is about 1.2 cm. According to Freidberg [8], Δ can be written as

$$\Delta = \lambda\beta \frac{R_s^2}{R_T} \left[\frac{2\pi R B}{\mu_o I_z} \right]^2 \qquad (3)$$

where λ is a parameter depending on the diffuseness of the pinch (for our conditions, λ = 1.0), R_s is the radius of the copper shell, R_T is the major radius of the torus, B is the magnetic field strength at the wall and I_z is the r.m.s. value of the oscillating axial current. Inserting the parameters for our pinch, we obtain from eq. (3): Δ = 1.05 cm which is quite close to the measured value.

5. Magnetic Fields

The magnetic field distribution in the Curved Theta Pinch was examined by means of two small probes (coil diameter 1.5 mm, coil length 1.5 mm). The probes were inserted along a major radius, at the midplane of the discharge tube (Fig. 1). By making measurements with the probes located at various radial positions, it was possible to obtain $B_z(r,t)$ and $B_\theta(r,t)$ with good space and time resolution.

Fig. 3 shows radial profiles of the toroidal field component, B_z, at various times. Each experimental point represents an average of three measurements.Note the dip in the toroidal field, due to the presence of the dense plasma column. The dip remains visible up to about 3 µs. At later times, it gets smeared out because the experiment is not perfectly reproducible, i.e., the radial position of the plasma column is not always exactly the same. At 3.0 µs, we observe a toroidal shift, Δ = 1.1 cm in agreement with photographic observations.

Fig. 4 shows amplitudes of the oscillating field component, B_θ, as functions of radius, at various times. Note that the times indicated in the Figure are only valid for points at the walls. The interior points are delayed in time, with respect to the points at the walls, by a phase shift $\varphi(r)$ (Fig. 5). This is because the measurement was made by following the various B_θ maxima on their way from the walls into the interior of the discharge tube. Again, each point in the diagram is obtained by averaging over three measurements. For comparison, results of earlier measurements that were performed without limiters, are also shown in the Figure. Experimental conditions, as well as plasma density and temperature, were identical in the two cases, i.e., with and without limiters. Yet, the corresponding B_θ field distributions are quite different: With limiters, the B_θ amplitude varies roughly as $\frac{1}{r}$ in the outside regions, in agreement with theoretical calculations [6]. Without limiters, however, the $\frac{1}{r}$ dependence is limited to the neighbourhood of the inner wall (R = - 2.5 cm) and is completely absent between the plasma and the outer wall.

In order to determine the current density distributions, we have measured the phase shift, $\varphi(r)$ of the oscillating field component B_θ, as a function of radius. We find that this quantity is nearly constant in time. Typical results are shown in Fig. 5, where we have plotted the time of a particular B_θ zero-crossing as a function of radius. Again, the results of previous measurements, without limiters, are included in the Figure.

The current density j_z is computed from Maxwell's equation,

$$\mu_0 j_z = \frac{1}{r} \frac{\partial}{\partial r} (r B_\theta), \tag{4}$$

assuming

$$B_\theta(r,t) = \hat{B}_\theta(r) \sin[\omega(t + \varphi(r))]. \tag{5}$$

Upon insertion of (5) into (4), we find

$$\mu_0 j_z = \frac{1}{r} \left\{ \frac{\partial}{\partial r} (r \hat{B}_\theta) \sin[\omega(t+\varphi)] + r \hat{B}_\theta \, \omega \frac{\partial \varphi}{\partial r} \cos[\omega(t+\varphi)] \right\} \tag{6}$$

and the current density amplitude is given by

$$\mu_0 \hat{j}_z = \frac{1}{r}\left\{\left[\frac{\partial}{\partial r}(r\hat{B}_\theta)\right]^2 + \left[r\hat{B}_\theta \omega \frac{\partial \varphi}{\partial r}\right]^2\right\}^{1/2} . \qquad (7)$$

Using the measured functions $\hat{B}_\theta(r)$ (Fig. 4, t = 2.5 μs) and $\varphi(r)$ (Fig. 5) on the right hand side of eq. (7), we obtain j_z amplitudes as shown in Fig. 6.Note that the current density on the inner wall (R = - 2.5 cm) is very small, in both cases. On the outer wall (R = 2.5 cm), however, the current density is larger in the case without limiters and relatively small (down by a factor 3) in the case with limiters.

IV. Conclusion

Measurements in the Curved Theta Pinch Experiment have shown, in accordance with theoretical predictions [6] , that the distribution of the oscillating axial current can be influenced by using limiters. In particular, we have seen, that limiters tend to concentrate the current onto the dense plasma column thus reducing high frequency energy losses at the walls.

Finally, it should be mentioned that the Russians are using the "Curved Theta Pinch" concept on some of their Tokamaks with great success: At the Efremov laboratory in Leningrad, for example, they [9] have produced stable Tokamak discharges, with q-values less than unity, by using oscillating toroidal currents.

V. Acknowledgement

This work was supported by the "Fonds National Suisse de la Recherche Scientifique".

Figure Captions

Fig. 1 Schematic diagram of the experimental apparatus.

Fig. 2 Streak photographs showing the effect of the application of $\tilde{I}_z$.

Fig. 3 Radial profiles of axial magnetic field, B_z, at various times.

Fig. 4 Radial profiles of oscillating magnetic field amplitudes, $\hat{B}_\theta$, at various times.

Fig. 5 Radial profiles of B_θ-phase shift, $\varphi(r)$.

Fig. 6 Radial profiles of oscillating current density amplitude, $\hat{j}_\theta(r)$, showing the effect of limiters.

VI. References

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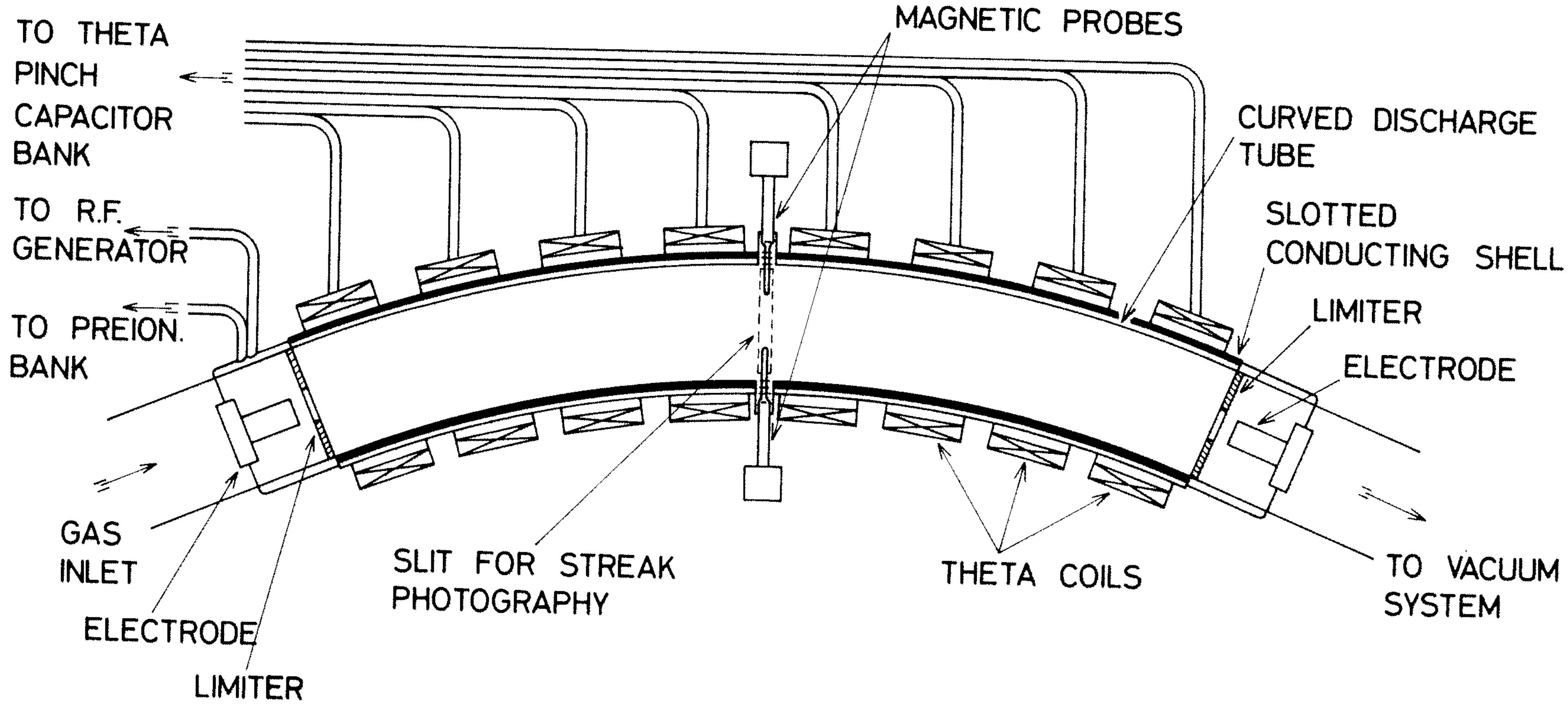

TO THETA
PINCH
CAPACITOR
BANK
TO R.F.
GENERATOR
TO PREION.
BANK
MAGNETIC PROBES
CURVED DISCHARGE
TUBE
SLOTTED
CONDUCTING SHELL
LIMITER
ELECTRODE
GAS
INLET
ELECTRODE
LIMITER
SLIT FOR STREAK
PHOTOGRAPHY
THETA COILS
TO VACUUM
SYSTEM

FIG. 1

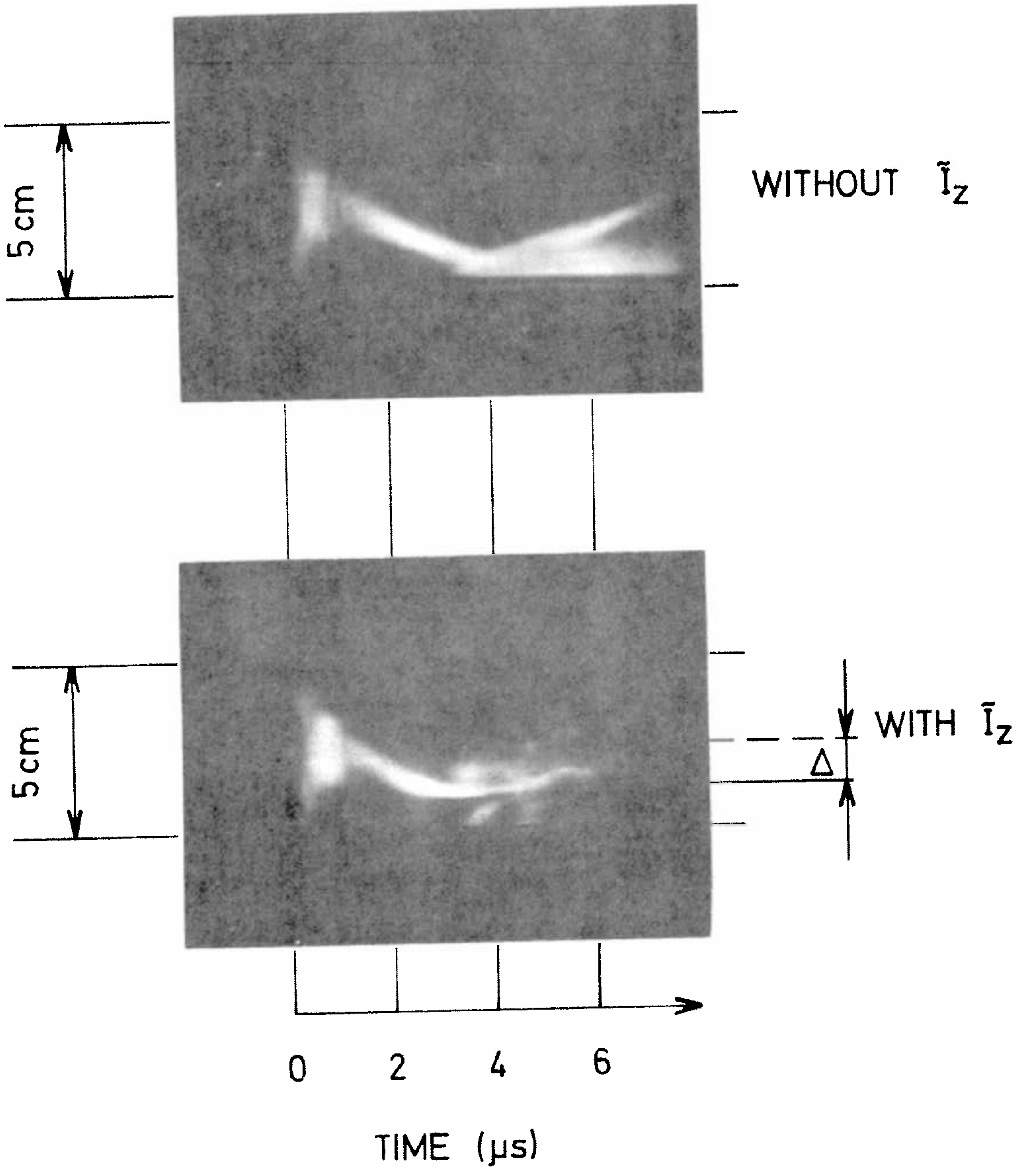
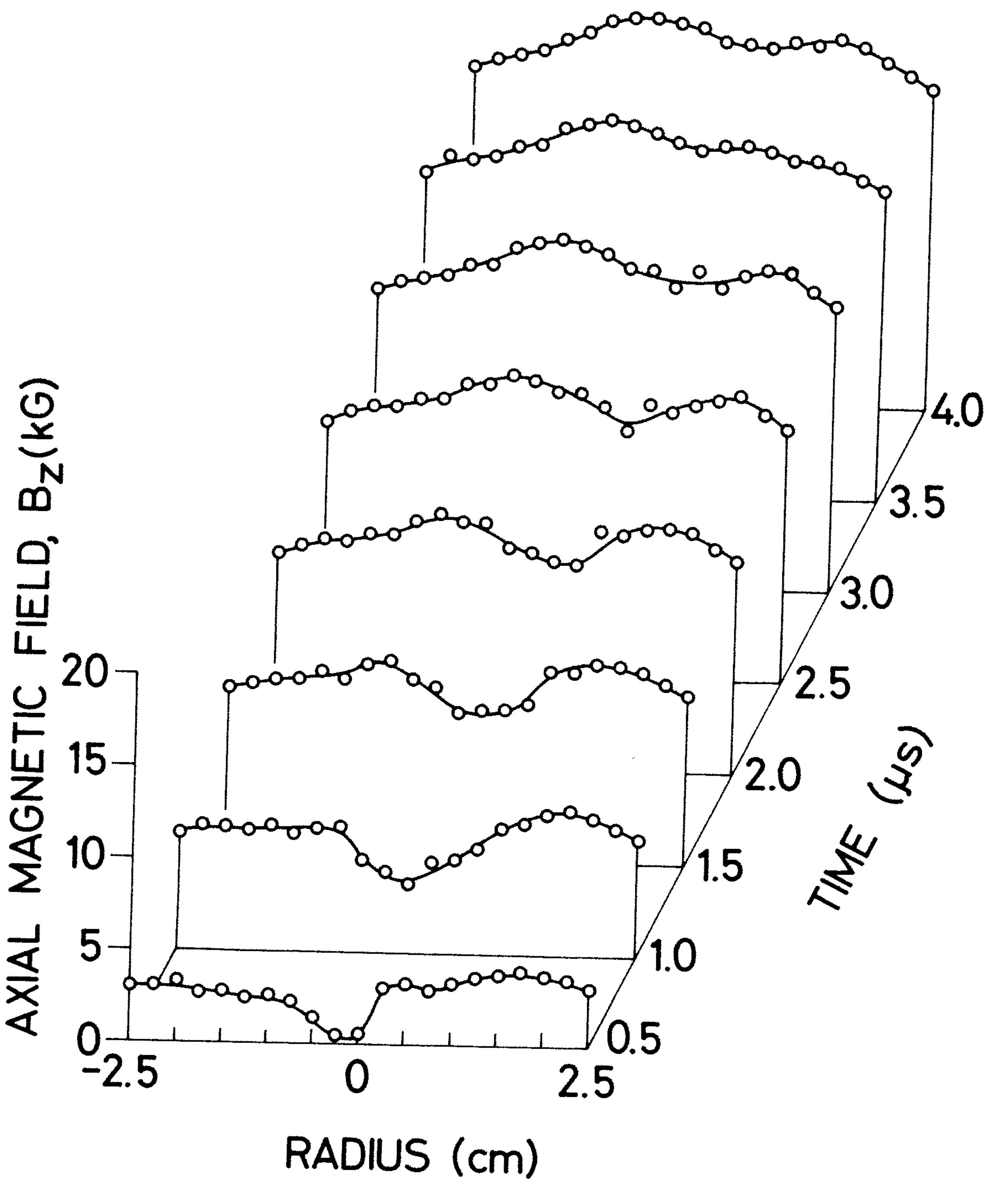


FIG. 2



AXIAL MAGNETIC FIELD, B_z(kG)
20
15
10
5
0
-2.5
0
2.5
RADIUS (cm)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
TIME (μs)

FIG. 3

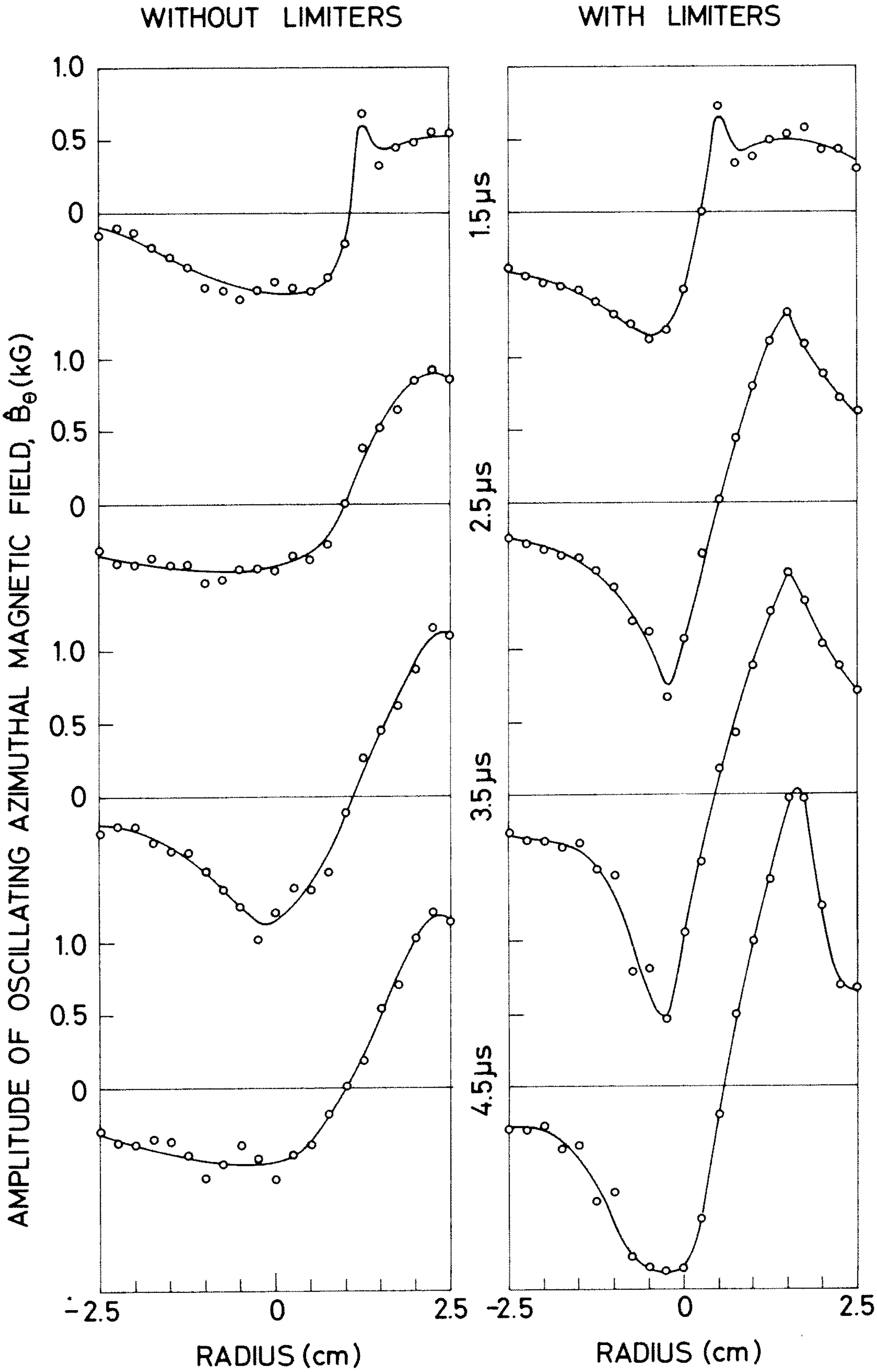

WITHOUT LIMITERS
WITH LIMITERS
AMPLITUDE OF OSCILLATING AZIMUTHAL MAGNETIC FIELD, $\hat{B}_\theta$ (kG)
1.0
0.5
0
1.5 μs
2.5 μs
3.5 μs
4.5 μs
-2.5
0
2.5
RADIUS (cm)

FIG. 4

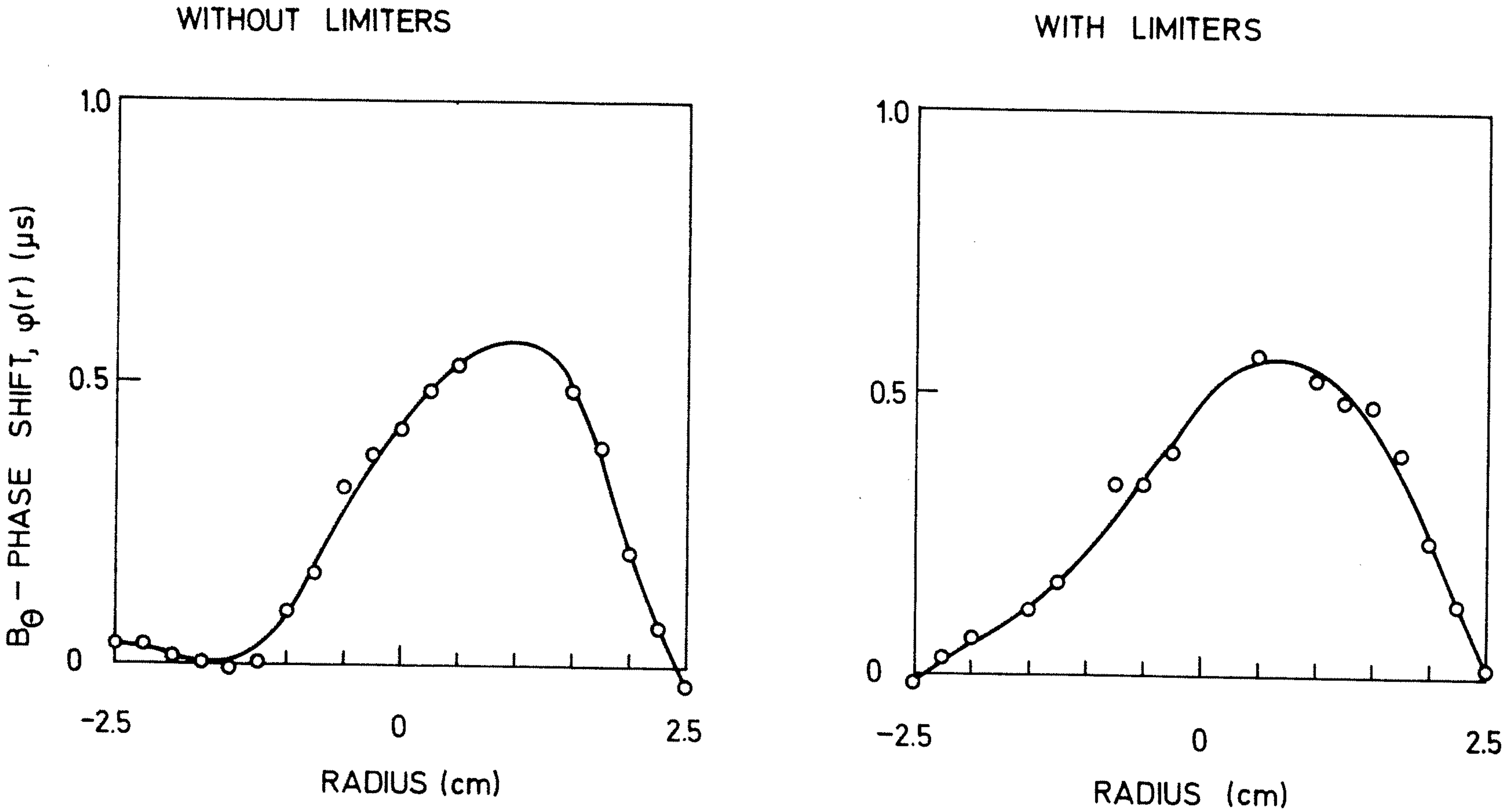

WITHOUT LIMITERS
WITH LIMITERS
Bθ – PHASE SHIFT, φ(r) (μs)
1.0
0.5
0
-2.5
0
2.5
RADIUS (cm)

FIG.5

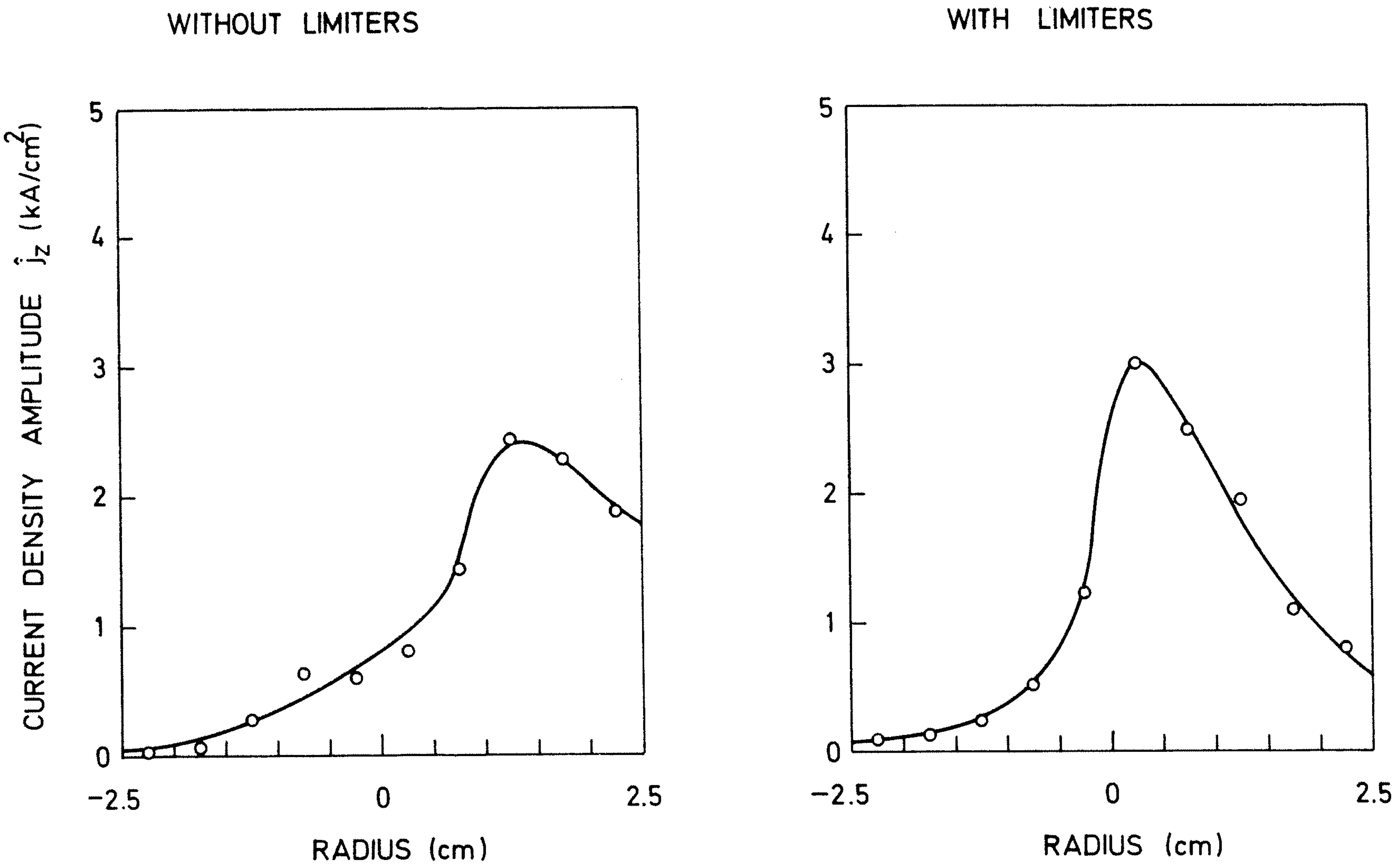

WITHOUT LIMITERS
WITH LIMITERS
CURRENT DENSITY AMPLITUDE $\hat{j}_z$ (kA/cm^2)
5
4
3
2
1
0
-2.5
0
2.5
RADIUS (cm)
RADIUS (cm)

FIG. 6